X-640-67-258

NASA TM X-55812

POLAR CAP ABSORPTIONS AND ASSOCIATED SOLAR-TERRESTRIAL EVENTS THROUGHOUT THE 19TH SOLAR CYCLE

BY

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JUNE 1967

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CONTENTS

	Page
1. Introduction	1
2. Polar Cap Absorptions and Associated Events in Years 1954-65	3
3. Relation Between PCA's and Type IV Solar Radio Outbursts	8
4. Solar Cycle Variations in the Corpuscle-activity of the Sun	10
5. Recurrent Geomagnetic Storms and Solar Cosmic Radiations	14
6. Conclusions	20
Acknowledgments	23
References	24
Table 1 – Outstanding Solar-terrestrial Events in 1954-65	

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ABSTRACT

Solar cycle variations in the high-energy-particle-emission of the sun is examined using daily PCA-indices, selected solar-terrestrial events, along with satellite observations of low energy solar protons, in the years 1954-65. A close relation between PCA's and type IV solar radio outbursts existed throughout the last solar cycle. The solar corpuscular activity showed three peaks in 1957, 1960, and 1963, giving an asymmetric Butterfly shape to the latitude-time distribution of type IV-sources. The first peak, which coincides with a sole maximum of sunspot numbers, is characterized by a random occurrence of type IV outbursts, PCA's, and geomagnetic SSC's. Active centers were restricted in two parts of narrow heliographic longitudes during the second, the most prominent peak, giving a slight 27 days-recurrence to the corpuscular activity. Finally, a pronounced peak of 27 days-recurrence appeared during the third period in spite of a rather decreased corpuscular emissivity. A recurrent series of solar Mev protons lasted for 15

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solar rotations, while those of geomagnetic Kp index and galactic cosmic ray intensity for 25 rotations. The appearance of recurrent Mev protons in the later phase of a solar cycle is controlled not only by the sector structure of the interplanetary space, but also more fundamentally by the energetic proton-productivity of the sun.

POLAR CAP ABSORPTIONS AND ASSOCIATED SOLAR-TERRESTRIAL EVENTS THROUGHOUT THE 19TH SOLAR CYCLE

1. Introduction

It has been known that the sun is an emitter of energetic particles which are the cause of various electromagnetic disturbances in the earth's upper atmosphere. In particular, during an intense solar flare, it emits not only a magnetized plasma cloud which is responsible for geomagnetic and galactic-cosmic-ray storms, but also, on occasions, very high-energy particles known as solar cosmic radiations.

Since the first observation of an unusual increase of cosmic rays in 1942 (Forbush, 1946), at least 14 events with proton-energy $E_p > 1$ Bev have been found by ground based observations. An arrival of sub-relativistic energy particles ($E_p = 1 \sim 1000$ Mev) is not detectable at the ground level, but this information is available from various space vehicles or indirectly from ionosphere observations. These particles emitted from a solar flare, precipitate upon the polar cap ionosphere, thereby producing an enhanced ionization that causes a severe absorption effect on radio waves. Thus the event is called the Polar Cap Absorption, or PCA. (Bailey, 1964; Hultqvist, 1963; Obayashi and Hakura, 1960). The occurrence of subrelativistic events is rather frequent, and almost two hundred outstanding events have been detected by various ionosphere observations since 1938 (c.f. Švestka, 1966; Basler and Owren, 1964).

As possible attributes of a cosmic-ray-flare, one may count several particular kinds of landscape or time-variation of the flare observed by various techniques, ranging from radio waves to γ-rays (Ellison, 1963; Kiepenheuer, 1964; Křivský, 1965 and 66). Among them, dynamic spectral features of solar radio outbursts provide the most promising tool for clarifying the nature of the cosmic-ray-flare. By statistical examination of solar radio outbursts and sub-relativistic solar protons in the last sunspot maximum, it has been shown that the emission of such high energy particles arises in close association with the occurrence of major type IV outbursts (Hakura and Goh, 1959; Thompson and Maxwell, 1960; Kundu and Haddock, 1960). The relation seems to be quite reasonable, because the type IV outburst is caused by a synchrotron radiation due to highly accelerated electrons spiralling in the solar magnetic field, and at the same time the generation of high energy protons in the excited solar atmosphere can be expected (Boischot and Denisse, 1957).

Satellite observations in a later half of the last solar cycle, however, have revealed numerous increases of low energy solar protons (E_p = 100 kev ~ 10 Mev) that had apparently little correlation with the type IV radio outbursts. Some of these observations have shown that the Mev-protons were confined within a region co-rotating with the sun which modulated the geomagnetic activity and the galactic cosmic ray intensity on the orbit of the earth with a 27 days period (Bryant, Cline, Desai, and McDonald, 1965; Fan, Gloeckler, and Simpson, 1965). The appearance of recurrent geomagnetic disturbances has been known as a prominent feature of the earth storms in the decreasing phase of the sunspot activity (Sinno, 1964).

The solar cycle variation in solar particle radiations is surely one of the most interesting subjects in the field of solar-terrestrial relationship. It has been known that no relativistic solar cosmic rays was observed during the maximum sunspot activity (c.f. Obayashi, 1964). Svestka, (1966), tracing PCA events back to 1938, has shown that the sub-relativistic particles also tend to avoid the top of sunspot activity during the last three sunspot cycles. Here, a question arises, "Is the sunspot number a unique measure of solar activity?" The importance of this problem has been emphasized, by Gnevyshev (1963) who showed the existence of two peaks of a coronal line intensity observed in the course of the last solar activity. The purpose of the present paper is to make a complete list of PCA's and associated solar-terrestrial events during the solar cycle 19th, on a basis of reasonably uniform criteria, and reexamine their casual relationship in various phases of solar activity. Three distinguishable peaks of solar corpuscular activity that appeared in 1957, 1960 and 1963 will be discussed.

2. Polar Cap Absorptions and Associated Events in Years 1954-65

2.1 Daily Indices of fmin-increase

As useful detectors of the PCA, we may count various ionosphere observations, such as VHF forward scatter transmissions, riometers, vertical absorptions, trans-polar-cap VLF transmissions, and fmin of vertical ionosphere sounders (c.f. Sawyer, et. al., 1966). Among them, the fmin, minimum observable frequency on vertical sounding ionogram, has some advantages in the world-wide coverage of observing stations and the retrospectivity due to its long observational history.

The value of fmin increases when an abnormal ionization is produced in the polar cap ionosphere by precipitating solar cosmic radiations. When all ionosphere echos are completely absorbed by an intense ionization, such condition is called the "blackout". As an example, a solar-geophysical event, that of August 16, 1958, is plotted in Fig. 1. On that date an intense flare of importance III+, associated with a major type IV radio outburst, occurred at 04:32 U.T. Simultaneously with the onset of the flare, a Sudden Ionosphere Disturbance (SID) was noted in an fmin observation at Alert, Canada; this is attributed to an excessive solar X-ray burst emitted from an excited coronal condensation at the time of the flare. A few hours after the SID, an increase in fmin value started again, indicating the onset of a PCA event. Concurrently, an incidence of solar cosmic-ray protons of energies 10-100 Mev was detected by a direct measurement of energetic particles by Explorer 4 in its orbit. The enhancement of fmin values lasted for about 3 days.

A general mophology of PCA's has been established on a series of synoptic studies of outstanding events observed during the IGY 1957-58, when an extensive observing network was in operation (Hakura, et al., 1958; Obayashi and Hakura, 1960; Hakura and Nagai, 1964; Hakura, 1957). The results have shown that the stations with invariant geomagnetic latitudes greater than 80° are safe from any influence of the auroral zone absorptions, and thus can be a reliable monitor of PCA events. Canadian data are especially useful because of their long history of observation since 1949. A number of PCA events have been noted by an examination of fmin-time series of Canadian stations (Jelly and Collins, 1962; Jelly, 1963).

In the present paper, daily indices of PCA activity were computed for Resolute Bay, Canada (84.3° in corrected geomagnetic latitude, Hakura, 1965), using the following definitions:

N_4 = number of hours per UT day with fmin $\geq$ 4 Mc/s, and

N_2 = number of hours per UT day with fmin $\geq$ 2 Mc/s.

The indices thus obtained can be a measure of PCA-producing solar cosmic rays, since they indicate some lower limits of total solar cosmic ray flux in certain energy ranges, impinging upon the polar cap during a day.

The indices were computed for years 1954-65, and the results are displayed on 27 days – recurrence tables in Fig. 2, where the indices are coded into 5 grades shown at the left of each table. When the Resolute Bay data were not available, those from Thule, Greenland were supplemented for the missing date. The tables show a general feature of PCA-activity in the whole solar cycle, observed with two grades of sensitivities.

2.2 Outstanding PCA Events for Years 1954-65

Using the fmin indices, outstanding PCA events for years 1954-65 were selected. In the middle of Table 1, which is given at the end of the present paper, are shown various information of PCA's, such as onset date and time in UT, delay-time from an associated flare Δt_a, approximate duration in days, importance, and type.

The importance of a PCA is determined from the fmin indices according to the following criterions:

Importance	Criterion
III	When $N_4 \geq$ 10 for $\geq$ 3 successive days
II	When $N_4 \geq$ 10 for 1 or 2 days
I	When $N_2 \geq$ 10 for $\geq$ 1 day
I-	When under I, but definitely identified as a PCA from other reliable sources.

Examples of PCA's of importance I, II, and III are shown in Fig. 3.

The onset time of a PCA is determined with consultation of fmin records of 15 minutes interval and riometers at several polar cap stations. Sometimes, the onset time was quoted from former publications such as Hakura and Goh (1959), Obayashi and Hakura (1960), Sinno (1961), Obayashi (1962), and Yamamoto and Sakurai (1967).

PCA's are classified into three types according to their delay-times from the associated type IV-flare: F or fast-onset type($\Delta t_a < 8h$), S or slow-onset type ($\Delta t_a \geq 8h$), and others (no associated type IV outburst). A sign G stands for the ground level solar cosmic ray event with $E_p \sim$ 10 Bev.

2.3 Associated Events

Table 1 also includes information of solar flares, solar radio outbursts of type IV, and geomagnetic storms, which presumably have direct connection with the onset of PCA events.

(i) Solar Radio Outbursts of Type IV and Associated Solar Flares

A typical major outburst consists of micro-wave impulsive bursts and following outbursts of type III, II, $IV\mu$, IV_{dm}, and IV_m as shown in Fig. 4 (Takakura, 1963; Fokker, 1963, and papers cited there). Each of type IV outbursts are characterized by their continuous spectra with long durations. Thus, in order to obtain a uniform list of type IV outbursts, dynamic spectral observations with frequency range 10 - 10^4 Mc/s at at least 3 longitudinally well-distributed stations are needed. However, with some considerations we may be allowed to select type IV outbursts from single frequency observations with a few key frequencies, such as 200, 500, 3000, and 9000 Mc/s. Actually the selection of type IV outbursts in the present paper was based on the Netherland stations at Nera, Holandia, and

Paramaribo well distributed longitudinally, and to those at Toyokawa, Mitaka, Hiraiso, Berlin, Boulder, and Ottawa. The result was adjusted in comparison with "A List of Solar Radio Type IV Bursts in 1957 to 1963" made by Kai (1967). An importance A, B, or C was given to each of the outbursts according to their magnitudes. The outbursts with importance A are fully developed and very intense, while those with importances B and C are of medium and minor scale, respectively.

The onset time, location, and importance of a flare associated with the type IV outburst was shown on the left side of Table 1, along with the importance of the type IV outburst. The flare information was mainly obtained from CRPL-FB series, issued by ITSA, ESSA, Boulder, Colorado, USA.

(ii) Geomagnetic Storms

The onset date, time in UT, delay-time from the flare, importance, and type of an associated geomagnetic storm are given on the right side of Table 1. Most of them were quoted from the table of solar-terrestrial events made by Hakura and Goh (1959), Obayashi (1962), Yoshida (1965). Reports of the Geomagnetic and Geoelectric Observations, 1954 through 1965, issued by Kakioka Magnetic Observatory, Japan, and lists of geomagnetic storms in Journal of Geophysical Research were also used.

It is almost impossible to make a complete list of solar-terrestrial events, that could convince all of researchers. Some of minor events selected in our table might be different from those made by others. However, the events listed in Table 1 can safely be used for statistical analysis of the solar-terrestrial relationship, since they have been selected on a reasonably uniform criteria.

3. Relation Between PCA's and Type IV Solar Radio Outbursts

In what follows, statistical examination will be made on the relation between type IV and PCA's observed in a period of 1956-65, where both observations are equally available.

(i) PCA-Producing Probability of Type IV Outbursts

In the second and the third columns of Table 2-1, are shown the number and percentage of type IV outbursts associated with PCA's. Among 116 outbursts, 87 events, i.e. 75%, were followed by PCA's. Moreover, among 29 outbursts without PCA, 22 events, i.e. 73%, were minor events of importance C, and major outbursts of importance A were always followed by PCA's, as shown in Table 2-2.

Table 2-1
PCA-Producing Probability of Type IV
Outburst for Years 1956-65

	With PCA	Without PCA
Number of type IV	87	29
%	75	25

Table 2-2
29 Type IV Outbursts Without PCA

Magnitude of Type IV	A	B	C
Number	0	7	22
%	0	27	73

(ii) PCA's Associated with Type IV Outbursts

In the second and the third columns of Table 3-1, are shown the number and percentage of PCA's associated with type IV outbursts. Among 131 PCA's, 87 events, i.e. 66%, were related to type IV outbursts. Among 44 PCA's that cannot be related to any type IV outburst, 30 events, i.e. 68% were minor PCA's of importance I.

Table 3-1
PCA Associated with Type IV Outburst

	With Type IV	Without Type IV
Number of PCA	87	44
%	66	34

As a result, it is evident that a close relationship between type IV out-bursts and PCA's, pointed out by Hakura and Goh (1959) using the IGY data, holds especially for events of major importance.

The correlation between both events is increased, when propagation conditions for PCA-producing particles in the interplanetary space are considered. Actually, our data have confirmed the east-west longitudinal asymmetry of PCA-producing probability as well as the deficiency of PCA-occurrence in the northern winter months, of which a number of discussions were made so far (see Obayashi, 1962; Švestková and Švestka, 1966, and papers cited there).

Table 3-2
44 PCA's Without Type IV Outburst

Importance of PCA	III	II	I
Number	1	13	30
%	2	30	68

Let us denote for a certain time or space interval:

N(O) = the number of type IV outbursts which did not produce any PCA event and

N(P) = the number of type IV outbursts which produced PCA events,

Then, the PCA-producing probability, P, is defined as

$$P = N(P)/N(P) + N(O).$$

Figure 5 shows PCA-producing probabilities of type IV outbursts in six heloographic longitude intervals. The well-known east-west asymmetry is evidently seen, suggesting that the twisted interplanetary magnetic field gives a more favorable propagation condition to the solar cosmic rays originating in the western part of solar disk than to those in the eastern part.

Figure 6 shows seasonal variations in (A) PCA-producing probability of type IV outbursts, P, (B) number of PCA's with type IV outbursts, N (P), and (C) number of type IV outbursts, N (P) + N (O), for years 1956-65. The PCA-producing probability shows a definciency in the northern winter month, though the probability was obtained by excluding a by-chance-seasonal variation of type IV outbursts shown in (C). The deficiency exists even after making correction for a seasonal effect using data from the southern hemisphere.

4. Solar Cycle Variations in the Corpuscle-Activity of the Sun

Figure 7 shows variations in (A) annual mean of Zürich sunspot numbers, (B) occurrence frequency of type IV outburst per year, and (C) number of PCA (total, identified ground level events of solar cosmic radiations, fast, and slow type events) for years 1954-65. It is easily seen that variations of type IV outbursts and PCA's are roughly parallel throughout the whole solar cycle, showing again that principal cause of solar cosmic radiations responsible for PCA's is a flare with type IV solar radio outbursts. The affinity is especially close between the occurrence frequencies of type IV outbursts and fast onset type PCA events, while most of well-defined PCA's of slow onset type occurred near the maximum of the sunspot number curve.

An interesting subject seen in Fig. 7 is three peaks of occurrence frequency of PCA's in 1957, 1960, and 1963, respectively, in contrast with the uni-maximum curve of Zürich sunspot numbers. The existence of two major peaks in 1957 and 1960 has been known by several workers including Sawyer et. al. (1966), Švestka (1966), and Gnevyshev and Křivský (1966). Švestka, tracing back PCA events for last 3 sunspot cycles, related these two peaks to a general tendency that the peaks of occurrence frequency of PCA's avoided the top of the solar activity curve. The tendency is especially evident for the GLE (ground level events of solar cosmic radiations) as seen in Fig. 7. Gnevyshev and Křivský connected the sunspot cycle variation of PCA's with those of coronal intensity by showing that proton flares develop in regions of enhanced coronal brightness, which showed two maxima in 1957 and 1960 (Gnevyshev and Ol', 966).

In the present paper, we have our own list of PCA and related events selected on somewhat uniform criterion throughout the last sunspot cycle. It is worthwhile of making a further detailed study of their solar cycle variation.

Figure 8 shows (A) heliographic latitudes of PCA-producing flares and (B) annual occurrence frequencies of northern and southern flares for years 1954-65.

In his survey of "Solar disturbances associated with PCA events", de Jager (1966) called our attention to the north-south asymmetry of flare activity, that more PCA-sources were found to occur in the northern solar hemisphere than in the southern during the last three cycles. More detailed structure of the north-south asymmetry are seen in Fig. 8(B); There are three peaks in the occurrence frequency of PCA-producing flares in the northern hemisphere, while the one in the southern hemisphere showed a peak in 1958.

The distributions of PCA-flares in latitude shown in Fig 8(A) is interesting in comparison with Maunder's Butterfly diagram. Examining the latitude distribution of sunspots from 1874 to 1913, Maunder (1922) showed that the first spots of a cycle occur at about 30°N and S. At sunspot maximum the zones reach ±15° latitude, while the last spots of a cycle appear at about ±8°. The pattern obtained here seems to show details of the Maunders' diagram; the northern diagram consists of 3 (or 2) separate parts, while the southern distribution shows single butterfly pattern. This result together with the one in (B) suggests that the last solar cycle consists of 2 outstanding and one rather small peak of activity, in 1957-58, 1960, and 1963, respectively.

We have often seen a localization of PCA-producing centers on the solar disk. For example, three outstanding PCA events were observed in July 1959, in association with three flares that occurred successively in the same MacMath plage region, on July 10, 14, and 16. It is interesting to examine the absolute longitudinal distribution of PCA-sources during the whole course of solar activity.

Let us denote:

d = date of flare observation expressed by (date + hour/24), and

λ = apparent heliographic longitude of the flare.

Then, the data of CMP (central meridian passage) of the flare is given

$$d' = \left(d - \frac{27}{360}\lambda\right).$$

Figure 9 shows the distribution of CMP date of PCA-producing flares in the northern and southern hemispheres, on a chart of 27 solar rotation day. On the whole, there is certainly a tendency that the PCA-flares occur in the same active region even for a few solar rotation periods.

Figure 10-(IV) summarizes the longitudinal distribution of the CMP dates for solar rotation numbers 1697 – 1795, i.e. July 24, 1957 through October 17, 1964. It is seen that there are (1) two inactive regions on the 2nd-6th days and 17th day, as well as (2) four active regions on 8th-9th, 12th-17th, 19th-20th, and 23rd-24th days, during the whole period of the last solar activity. Fig. 10-(I) through (III) gives the distributions in three different phases of solar activity: (I) solar rotation numbers 1697-1719, July 24, 1957 – March 6, 1959, (II) solar rotation numbers 1720-1764, March 7, 1959 – July 3, 1962, and (III) solar rotation numbers 1765-1795, July 4, 1962 — October 17, 1964.

In the period (I) which included the first peak of PCA-activity, there were at least four active center and their longitudinal distribution looks rather random. On the other hand, the active regions were restricted in 2 parts of narrow heliographic longitudes in the periods (II) and (III) (c.f. Sakurai, 1966), though the positions of active regions were somewhat different in the two periods. The localization of activity was especially outstanding in the period (II) which included the second peak of PCA-activity.

It is believed that the interplanetary magnetic field is generated as a result of the transport of the solar magnetic field with the outflowing solar plasma. Then, the localization of solar active centers might mean the simplification of interplanetary field in the declining period of sunspot activity (II) and (III), from the complexity observed in the maximum period (1). Actually, in 1963, the satellite IMP-I revealed a simple sector pattern of the interplanetary space that lasted for more than several solar rotations (Ness, et. al., 1964).

5. Recurrent Geomagnetic Storms and Solar Cosmic Radiations

Figure 11 shows sunspot cycle variations in (A) annual mean of ΣKp, (B) 27 days autocorrelation coefficient of ΣKp, and (C) numbers of two different kinds of geomagnetic storms, SC- and G-types, observed at Kakioka, Japan. The SSC's occur rather sporadically and may be connected with the onset of major flares in the central regions of the solar disk. The SG's start gradually, last for a week or so, and sometimes recur with some 27 days period.

What is obvious in Fig. 11 is two sets of affinity between (1) ΣKp and SSC, and (2) autocorrelation coefficient and SG. It is easily seen that two outstanding peaks of ΣKp in 1957 (I) and 1960 (II) are mainly due to the occurrence of SSC's. Because of sporadic nature of the SC storm, the 27 days autocorrelation coefficient of ΣKp showed very low value during the first peak of geomagnetic activity, 1957-58. A slight enhancement of the coefficient seen in 1960 (II) is due to the locality of flare-sources discussed in Fig. 10. Since the geomagnetic storm-producing probability shows a maximum at the CMP of source-flares, the locality of type IV sources causes some recurrency in spite of sporadic nature of the flare-occurrence itself.

Another interesting problem seen in Fig. 11 is an inverse relation of ΣKp value to its recurrency, in 1961-64. It is known that the ΣKp value is linearly related to a daily average of solar wind velocity (Snyder, et al., 1963) and the interplanetary magnetic field magnitude (Wilcox, et al., 1967). Thus, the inverse relation shows that a nice traffic regulation of 27 day period was established during the end of solar cycle (III) when the solar wind velocity and the interplanetary field became lowered.

Generally speaking, the 27 days autocorrelation coefficient of ΣKp showed a gradual increase toward the sunspot minimum form 1956 to 1964. The similar tendency is seen in the variation of G-type geomagnetic storms. If we assume the occurrence frequency of the SG as a representative of the recurrency, we can see a secular variation of the recurrency for 4 solar cycles from 1924 to 1965 in Fig. 12, where occurrence frequencies of SC storms, non-SC storms (SG's), and sunspot numbers are given. The non-SC recurrent storms show a saw-tooth distribution with 11 years period. This, along with a possible periodicity of 3 solar cycles, might afford a tool for long-term prediction of the recurrence.

Evidence for the 27-days-recurrent PCA was first shown by Gregory and Newdick (1964), and later criticized by Basler and Owren (1964) using 105 well defined events from Jan. 1957 to Feb. 1962. However, it is obvious from our results that the recurrence of PCA's should be examined for the data obtained during the low solar active period, when the geomagnetic recurrence becomes predominating. Figure 13 shows day to day variations in N_2 and N_4 indices for 6 solar rotations 1773-78. This period is especially interesting, since Bryant et al. (1965) have presented a clear recurrence of Mev proton events using the Explorer XIV satellite data. Associated phenomena such as solar flares, type IV solar radio outbursts, and geomagnetic storms are indicated by the symbols shown in the top of the figure. Except for a type IV-associated event on April 15, 4 other detectable PCA events in the present period occurred with some 27 days recurrence, starting on 5th-6th days of the table. If we assume these PCA's as identical with Mev solar proton events, then the recurrent events persisted for the whole period considered here.

Figure 14 shows the relation between the Mev proton flux given by Bryant, et al. and N_2 index of PCA's obtained from Fig. 13. Among 9 events, 8 proton events are well above the threshold value, while only 6 events can be identified as PCA's (4 definite PCA's of Imp. I, a PCA of Imp. I-, and a doubtful PCA of Imp. I--). The result clearly shows a superiority of the satellite data to the ionospheric absorption measurement for the detection of solar Mev proton events during the low solar active period. In recent years, measurable energy range by space vehicles goes lower and lower, and numerous increases of solar cosmic ray intensity have been detected, for example, by the IMP-1 with 1 Mev proton detector (Fan et. al., 1965), and by the Mariner IV with 0.5 Mev detector (Krimigis and Van Allen, 1966). These data together with fmin data, which has still an advantage in its retrospectivity or availability for a long period of time, will afford a nice tool to examine the recurrence tendency in the low sunspot activity.

All of low energy proton observations for solar rotations 1767 through 1811 are shown on 27 days recurrence table in Fig. 15 - left, where, B means Bryant et. al., F Fan et. al., K Krimigis and Van Allen and f fmin index $N_2 \geq 4$. It is seen that the recurrent series starting from the 5th-6th days is a really clear one lasting for more than 15 solar rotations in 1963-64. Figure 15 - right, shows 27 days recurrent table for the geomagnetic ΣKp index, digitized into 6 grades shown at the top of the table. In this case the recurrence lasted for about 25 solar rotations from the end of 1962 to the end of 1964.

An average feature of low energy proton events along 27 days for solar rotation 1767-84 is shown in Fig. 16: (A) the occurrence frequency of Mev proton events, and (B) that of N_2 index of PCA. In comparison, are shown average 27 days variations in (C) geomagnetic ΣKp index and (D) neutron intensity at Deep River, and occurrence frequencies of (E) type IV outbursts and (F) CMP dates of the source regions. Predominating peaks observed from the 5th to 12th days in in (A) and (B) are due to the recurrent series of solar Mev proton events. This series coincides with those of (C) geomagnetic ΣKp-index and of (D) neutron intensity variations, which have been reported as tracable for over 20 solar rotations (Mori, et. al., 1964). Thus, it can be said that the Mev protons were confined within a region corotating with the sun which causes an enhancement of geomagnetic activity and at the same time modulates the galactic cosmic radiations at the orbit of the earth with the 27 days recurrent period.

The distribution of type IV outbursts shown in (E) were almost uniform along the 27 days, telling that these recurrent events have no direct connection with any individual major solar flares. The distribution of CMP dates of type IV sources (F) shows that the recurrent series appeared a few days after the CMP of an inactive region of 23rd-3rd days, and entirely out of phase with the most active region of 12th day. Figure 17 is another expression of 27 days variations in ΣKp, N_2 index, and coronal green line G6 (quoted from Sinno, 1964, and Obayashi, 1964), as well as sector structure of interplanetary magnetic field observed by the satellite IMP-1 in the same period (Ness et. al., 1964). The dates 5, 10, 15, 20, and 25 are indicated along the ΣKp variation. The ΣKp and N_2 observed at the orbit of the earth are connected with the solar coronal data observed 4 days earlier, assuming a solar wind velocity of 500 km/s. It is evident that the maxima of ΣKp and N_2 index on the 7th day were situated at a sector boundary of the interplanetary magnetic field. This is consistent with a finding by Ness and Wilcox (1965) that the regions of high magnetic field intensity and high solar wind velocity always followed these corotating field reversal regions. As shown elsewhere (Hakura, 1964), a maximum of variance of the interplanetary magnetic field observed by Mariner II (Snyder, et. al., 1963) occurred at the leading part of the velocity enhancement, or at the field reversals.

The turbulence in the interplanetary field may be attributed to Kelvin-Helmholtz instability that developed along the velocity discontinuity (Dessler and Fejer, 1963) and the sheet pinch instability produced along the field reversal region (Sakurai, 1966). The twisted fan shaped region of the irregularity corotating with the sun might be the cause of the recurrent cosmic ray modulation.

The continual presence of Mev proton events, however, needs some particle-acceleration mechanism, and has been explained by the following hypothesis:

(1) The continuous acceleration of Mev protons exists at the bottom of a sector boundary.

(2) It does in an active region of the sun, and energetic particles produced are stored in the interplanetary magnetic field for a few solar rotations.

(3) It does in the interplanetary space in turbulent interface.

The first hypothesis seems to be unreasonable since they are connected with an inactive region of the coronal emission as shown in Fig. 17. The old active region proposed by Mustel (1961) can not be the root of the present sector boundary, since the 2nd-6th days remained inactive throughout the last sunspot cycle as shown at the top of Fig. 10.

For the second hypothesis, we had a pretty active region that appeared during the third period of PCA activity (III). Suppose that the region is connected with the turbulent region with a bottle-shaped interplanetary field, then the solar cosmic rays produced in the active region will propagate along and be stored in the magnetic bottle, especially in the turbulent magnetic region.

Statistics shown in Fig. 18 might give a support to the present hypothesis, where solar cycle variations in $\overline{N}_2$ and $\overline{N}_4$ indices (top), ratio $\overline{N}_2/\overline{N}_4$ (middle), and 27 days autocorrelation coefficient of ΣKp (bottom) are given. It is noted that variations in $\overline{N}_4$ and $\overline{N}_2$ were almost parallel during the high sunspot number, while the ratio $\overline{N}_2/\overline{N}_4$ became greater in 1961 through 1963. This shows that the Mev proton events represented by enhancement of N_2 index became predominant during the decreasing period of sunspot activity, when the recurrence of geomagnetic activity, ΣKp, also enhanced. However, an important point here is the difference between $\bar{N}_2$ and the autocorrelation coefficient in 1964. The PCA producing Mev proton was absent, $N_2 = 0$, while a still sound sector structure of interplanetary space existed as seen by a high value of the autocorrelation coefficient in 1964. The appearance of recurrent PCA's, i.e. Mev proton events is caused by the formation of a solid sector structure of the interplanetary space. However, it is also strongly controlled by the type IV activity discussed in Fig. 7.

As pointed out by Fan et al. (1965), the third hypothesis cannot explain the reason why not all the field reversing, corotating regions contain Mev protons at all times. However, it is interesting to note that the long-lived recurrent storms of galactic cosmic rays were observed only when the same sector boundary swept the earth. Though we do not have any evidence that supports the peculiarity of the present sector boundary, this hypothesis is still surviving.

6. Conclusion

Daily indices of PCA-activity were computed for years 1954-65, which covers the whole period of the solar cycle 19th. Outstanding PCA events were selected on the basis of the activity indices, and correlated with other solar-terrestrial phenomena, such as solar flares, type IV radio outbursts, and geomagnetic storms. A study of solar-terrestrial relationship was made using the daily indices, the table of outstanding events, along with satellite observations of low energy solar protons. Several important results obtained of the solar cycle variation in the corpuscular activity will be summarized as follows:

1. A close correlation between PCA's and type IV solar radio outbursts holds throughout the whole solar cycle considered here, especially for events of major importance.

The correlation was increased, when propagation conditions for PCA-producing particles in the interplanetary space were considered. A statistical study showed an east-west asymmetry of a PCA-producing probability of type IV sources, and also a deficiency of PCA-occurrence in northern winter months.

2. Solar corpuscular activity inferred from occurrence frequencies of PCA's and type IV outbursts showed three peaks during the last solar cycle, i.e. two outstanding peaks in 1957 (I) and 1960 (II), and a small peak in 1963 (III). During the first peak of activity (I), the type IV-sources appeared equally in both the northern and southern hemispheres of the sun. On the other hand, the active centers existed only in the northern hemisphere, during the later phases of solar activity (II) and (III). Consequently, the heliographic latitude time distribution of type IV-sources showed a complicated pattern with three wings in the northern hemisphere, which is different from the Maunder's simple Butterfly diagram obtained for sunspot regions.

3. There was a tendency that the PCA-flares occurred in the same active regions even for a few solar rotations. A statistic of the longitudinal distribution of CMP dates of the active centers showed that there were at least four active regions in the period (I), while the active regions were restricted in two parts of narrow heliographic longitudes in the periods (II) and (III). Throughout the whole solar cycle, there were two definitely inactive longitude-regions on the 2nd-6th days and 17th day of solar rotation.

The localization of active centers in the later phase of solar activity might be connected with a simple sector pattern of interplanetary magnetic field revealed by the satellite IMP-1.

4. The solar cycle variations in both the annual mean of geomagnetic ΣKp index and occurrence frequency of the SSC (geomagnetic storms with sudden commencement) showed two peaks in the period (I) and (II). Because of sporadic nature of the SSC-occurrence, the 27 days autocorrelation coefficient of ΣKp was very low for the first period (I). On the other hand, the locality of flare-sources caused an enhancement of the coefficient in the period (II).

The solar cycle variation in the SG-occurrence (the SG stands for a gradual geomagnetic storm) was similar to that in 27 days coefficients. Both of them increased toward the end of the solar cycle, and had a prominent peak in the period (III). The saw-tooth distribution of the non-SC recurrent storm occurred with 11 (and possibly 33) years-periodicity in the years, 1924 through 1965.

5. During the later phases of solar corpuscular activity (II) and (III), various space vehicles detected a number of solar Mev protons which sometimes caused a slight PCA event detectable by the daily PCA index of higher sensitivity (N_2). A recurrent series of the Mev protons starting from the 5th-6th days lasted for about 15 solar rotations in 1963-64. This series coincided with a part of recurrent series of geomagnetic ΣKp index and galactic-cosmic-ray variations, which were tracable for about 25 solar rotations, ranging from the end of 1962 to the end of 1964. The result means that the Mev protons were confined within a region corotating with the sun which caused an enhancement of geomagnetic activity and at the same time modulated the galactic cosmic ray intensity at the orbit of the earth with a 27 days recurrent period.

The maxima of ΣKp and Mev proton activity on the 7th day were situated at a field reversal region of the interplanetary magnetic field observed by IMP-1. The root of the field reversal region was identified with the persistently inactive region of PCA-productivity and coronal green line G6 intensity.

6. The appearance of recurrent PCA's or Mev protons is no doubt correlated with the formation of a solid sector structure of the interplanetary magnetic field. However, it is also strongly controlled by the productivity of low energetic solar protons of the sun. Our available materials seem to support a hypothesis that the continuous acceleration existed in an active region of the sun, and energetic particles produced were stored in the interplanetary magnetic field for a few solar rotations.

Acknowledgments

The author wishes to express his thanks to Drs. U. D. Desai, F. McDonald, and W. N. Hess of NASA, USA, Dr. D. H. Jelly of DRTE, Canada, Dr. K. Toman of AFCRL, USA, for their valuable discussions and comments.

The present work was carried out while the author held a senior postdoctoral resident associate of the NAS-NAE at the NASA-Goddard Space Flight Center, on leave of absence from the Radio Research Laboratories, Tokyo, Japan. He is grateful to Drs. W. N. Hess and T. G. Northrop for their hospitality.

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LIST OF ILLUSTRATIONS

Figure 1. Solar-terrestrial events on August 16-18, 1958.

Figure 2. 27 days-recurrence tables of daily PCA-activity indices, N_4 (left) and N_2 (right).

Figure 3. Three PCA events of different magnitudes as expressed by daily PCA-activity indices, N_4 and N_2.

Figure 4. A schematic dynamic spectrum of an intense solar radio outburst.

Figure 5. PCA-producing probabilities of type IV sources in six heliographic longitude intervals, inferred from the locations of associated flares.

Figure 6. (A) PCA-producing probability of type IV outburst, (B) Number of PCA's with type IV and (C) Number of type IV outbursts, for each month, January through December.

Figure 7. (A) Annual mean of Zürich sunspot numbers, (B), Number of type IV outbursts, and (C) Number of PCA's (total, identified GLE, fast-, and slow-onset types), for years 1954-65.

Figure 8. (A) Heliographic latitudes of PCA-producing flares and (B) Annual occurrence frequencies of northern and southern flares, 1954-65.

Figure 9. Distribution of CMP date of PCA-producing flares in the northern and southern hemispheres, on 27 days recurrence chart.

Figure 10. Longitudinal distributions of the CMP dates of type IV-sources, for solar rotation numbers (I) 1697-1719, (II) 1720-1764, (III) 1765-1795, and (IV) total.

Figure 11. Solar cycle variations in (A) annual mean of ΣKp, (B) 27 days autocorrelation coefficient of ΣKp, and (C) numbers of SC and G-type geomagnetic storms observed at Kakioka, Japan.

Figure 12. Occurrence frequencies of two kinds of geomagnetic storms per year, observed at Kakioka, and Zürich sunspot numbers, for the years 1924-65.

Figure 13. PCA's, Mev proton events, flares, type IV outbursts, and the SSC's observed in solar rotations 1773-78. A recurrent series of PCA's or Mev Proton events are notified by vertical dotted lines.

Figure 14. Relation between maximum flux of Mev proton events and maximum index of PCA given in Fig. 13.

Figure 15. 27 days recurrence tables of (A) low energy solar proton events and (B) geomagnetic Kp index, for solar rotations 1767-1811.

Figure 16. Occurrence frequencies of (A) Mev proton events and (B) N_2 index, average 27 days variations in (C) geomagnetic ΣKp index and (D) neutron intensity at Deep River (Mori et. al., 1964), and occurrence frequencies of (E) type IV outbursts and (F) CMP dates of source regions, for 18 solar rotations 1767-84, i.e. August 27, 1962 – December 25, 1963.

Figure 17. 27 days variations in ΣKp, N_2 index and coronal green line G6, and sector structure of the interplanetary space (Ness et al., 1964).

Figure 18. Solar cycle variations in (A) mean N_4 and N_2 indices, (B) ratio N_2/N_4, and (C) 27 days autocorrelation coefficients of ΣKp.

Table 1
Outstanding Solar-terrestrial Events in 1954-65

Year	Month	Solar Flare with Type IV Outburst: Onset Date	Time	Position	Imp.	Imp. of Type IV	Polar Cap Absorption: Onset Date	Time	Δt_a (hrs)	Duration (days)	Imp.	Type	Geomagnetic Storm: Onset Date	Time	Δt_m (hrs)	Imp.	Type
1954	V						1	0200		3	I						
	VIII						19			13	I						
1955	I						16			2	II		17	0322		II	SSC
	II						1	0900		1/2	I						
	XI						19	1200		1/2	I		19	1319		II	SSC
	XII						6	0400		1	I		5	2216		I	SSC
1956	II	14	0541			B											
	II	23	0334	N23W74	III+	A	23	0415	0.7	3	III	G,F	25	0307	48	III+	SSC
	III						10	1400		7	II		10	1058		II	SSC
	IV						15	0100		1	I		15	1628		I	SI
	IV	27	2100	N15W34	II	C	27	2200	1	1	II	F	30	0138	53	III	SSC
	V						14	0500		1	I		13	2222		III	SSC
	VIII						28	2300		1	I						
	VIII	31	1228	N18E12	III	A	31	1500	2.5	4	III	F	IX/02	0230	38	III+	SSC
	XI						8			3	I		9	2030		III	SSC
	XI	13	1431	N16W10	II	C	14	[b]0000	9.5	3	II	S	15	0807	42	III	SSC
	XII						25			3	I		25	0754		I	SSC
1957	I	(20	1116	S25W18	III)		20	2215		4	II		21	1255		III	SSC
	II	(21	1605	N13W40	III+)		21	1800		3	II		23	1807		III+	SSC
	III						28	0900		2	I		29	0336		I	SSC
	IV	3	0825	S15W60	III	C	3	1015	2	7	III	F	5	1436	54	II	SI
	IV						11	1300		7	II						
	IV	16	1048	N32E90	II	C											
	IV	17	2000	N12E70	III+	C							17	2332	37	I	SI
	IV						19	0200		3	I		18	1508		III+	SSC
	V						5	0200		2	I						
	V						8	0100		4	I						
	V						30			3	I		30	0822		II	SSC
	VI	19	1608	N20E46	II	C	19	2215	6	6	III	(F)					
	VI	(22	0236	N23E12	II)		22	0500		6	III		24	0340		II	SSC
	VII	3	0712	N14W40	III+	B	3	0930	2	4	III	F	5	0042	42	III	SSC
	VII	16	1740	S33W28	III	C	19			2	I		19	0519	60	I	SSC
	VII	24	1816	S24W22	III	C	24	2015	2	1	I	F	27	1959	74	I	SSC
	VII	(28	1346	S24W75	III)		28	1500		1	I						
	VIII	(9	0609	S09E75	II)		9	1500		3	II		12	1135		III	
	VIII	28	0913	S30E35	III+	C	28	2230	13	>3	III	S	29	1920	34	III	SSC
	VIII	31	1257	N20W02	III	C	31	1415	1.5	>3	III	F	IX/2	0314	38	III+	SSC
	IX	2	1257	N11W26	I+	B	2	1500	2	3	III	F	4	1300	48	III+	SSC
	IX	11	0243	N11W03	III	B	12	08	29	2	I	S	13	0046	46	III+	SSC
	IX	12	1520	N10W19	II	C	12	Masked			I						—
	IX	19	0400	N23E01	III	C	19	08	4	2	I	F	21	1005	54	III+	SSC
	IX	21	1340	N10W08	III	C	21			3	II	F	22	1345	24	III	SSC
	IX	26	1907	N26E15	III	C	26	2315	4	2	I	F	29	0016	53	I	SSC
	X	20	1637	S25W45	III+	B	21	05	12	2	II	S	21	2241	30	II	SSC
	XI	(5	0203	N38W63	II)		5	0700		1.5	I		6	1821		III+	SSC
	XI	24	0850	S13E37	III	C							26	0513	44	II	SSC
	XII	13	0215	N22E90		C											
	XII	14	1100	(N17E75	II)	C											
	XII	17	0734	N22E44	II+	C	17	1200	4.5	1	I	F	19	0937	50	II	SSC
1958	II	9	2108	S13W14	II	A	10	0700	10	2	II	S	11	0125	28	III+	SSC
	III	1	0340			C							3	0931	54	I	SSC
	III	(11	0048		III)		11	0500		2	II		14	1212		I	SSC
	III	14	1508	S23W80	III	C	14	1600	1	2	II	F	17	0750	65	I	SSC
	III						18			16	II		17	0751		I	SSC
	III	23	0950	S14E77	III+	B	25	08	46	>8	III	S	25	1540	54	I	SSC
	IV						10	06		3	II		11	2140		I	SI
	VI	4	2140	N15W58	II	C	5	04	6	2	I	F	7	0046	51	III	SSC
	VI	6	0436	N15W77	III	C	6	1345	9	2	I	(S)	8	1728	61	I	SSC
	VI	26	0300	N10E49	II+	B							28	0713	52	I	SSC
	VII	7	0039	N24W09	III+	B	7	[b]0200	1.5	6	III	F	8	0748	31	III+	SSC
	VII	29	0303	S14W43	III	B	29	[b]0415	1	2	I	F	31	1532	60	I	SSC

Year	Month	Solar Flare with Type IV Outburst					Polar Cap Absorption						Geomagnetic Storm				
		Onset Date	Time	Position	Imp.	Imp. of Type IV	Onset Date	Time	Δt (hrs)	Duration (days)	Imp.	Type	Onset Date	Time	Δt (hrs)	Imp.	Type
1958	VIII	16	0432	S14W53	III+	A	16	[b]0715	2.5	3	III	F	17	0622	26	III	SSC
	VIII	20	0043	N16E23	III	C	21	1445	38	>1	II	S	22	0227	50	II	SSC
	VIII	22	1417	N18W09	III	C	22	1530	1	>4	III	F	24	0140	35	III	SSC
	VIII	26	0005	N20W54	III	A	26	0215	2	4	III	F	27	0303	27	III	SSC
	IX	14	0830	S10W71	III+	C	14	1045	2	1	I	F	16	0930	49	III	SSC
	IX	(22	1012	N17W65	II–)		22	1430		3	II		25	0408		III+	SSC
	X	21	2330	S02W20	II	B							22	20--	21	III	
	X	24	1440	S04W57	III	C							27	1523	70	III	SSC
	XII	12	1300	S05W07	II	C							13	1148	23	III+	SI
	XII	23	0540	S16E65	III	C							25	2330	66	II	SI
1959	I	7	0245	S12W03	I	C							9	1459	60	III	SSC
	I	(26	0013	N09W42	II)		26	14		2	I		27	1329	37	I	SSC
	II	9	0200	N13E90	II	C							11	0318	49	II	SSC
	II	12	2300	N12E48	III+	C	13	[b]10	11	4	I	S	14	1142	37	II	SSC
	V	10	2055	N23E47	III+	B	11	0130	4.5	13	III	F	11	2328	27	III	SSC
	V	11	2010	N08E39	II+	C		Masked			III	F	12	1537	20	II	SI
	V	13	0510	N22E26	II	C		Masked			III	F	15	0703	50	II	SSC
	VI	09	1651	S20E00	III+	B	(10	0045	8	1	I	S)	11	0909	40	I	SSC
	VI	(13	1051	N17E27	II)		13	13		4	I						
	VII {	9	2030	N18E67	I	B											
	VII {	10	0210	N22E70	III+	A	10	0615	4	>4	III	F	11	1625	38	II	SSC
	VII	14	0342	N16E07	III+	A		Masked		>3	III	F	15	0803	28	III+	SSC
	VII	16	2115	N08W26	III+	A		Masked		9	III	F	17	1638	19	III	SSC
	VIII						2			4	I	F					
	VIII	14	0130	N12E28	II+	C							16	0404	50	III+	SSC
	VIII	18	1022	N11W34	III	C	18	13	12.5	2	II	F	20	0412	42	I	SSC
	IX	01	1924	N12E60	II+	C							03	1417	43	I	SSC
	XI	30	0250	N08E16	II	B											
	XII	21	0050	S03W53	I	C	(21	(06)	(5)	1	I-	F)	23	1525	62	II	SSC
1960	I	11	2040	N23E05	III	C	12			2	I		13	1859	46	II	SSC
	I	15	1340	S20W66	II	C							16	2114	31	I	SSC
	III	29	0650	N12E31	III	A	30	[b]1000	27		I	(S)	31	1036	52	III+	SSC
	III	30	1520	N11E15	II+	B		cont after SID		>2	III	F	31	2142	30	III+	SSC
	IV	1	0845	N13W09	III	C	1	1000	1	>4	III	F	2	2313	39	III	SSC
	IV	5	0215	N12W62	III	A	5	10	8	2	II	S	6	1628	39	I	SI
	IV	28	0130	S05E34	III	C	28	0400	2.5	1	II	F	30	0132	48	II	SSC
	IV	29	0209	N10W22	III	A	29	0600	4	3	III	F	30	1213	32	III+	SSC
	V	4	1015	N12W90	III	B	4	1045	1/2	1	I	G,F	6	1719	55	II	SSC
	V	6	1404	S10E08	III+	C	6	[b]2030	6	3	III	F	8	0421	42	II	SSC
	V	(9	0704	S10E55	III+)		9	11		2	II		11	0435		II	SSC
	V	12	1340	N30W60	I	C	12			1/2	I	F					
	V	13	0522	N30W64	III+	A	13	0845	3	2	II	F	16	1351	80	II	SSC
	V						17	21		1	I						
	V	26	0851	N14W15	II	C	26			3	I		28	2029		I	SI
	VI	1	0830	N28E46	III+	C	1	12	3.5	5	II	F	3	1731	57	II	
	VI	25	1200	N22E05	III	C							27	0145	38	IV	SSC
	VI	25	2040	N18W04	III	C							27	1630	44		
	VI {	27	0010	S7E35	III	C											
	VI {	27	2140	N17W28	III	C	28			2	I		29	1939	46	III	SSC
	VI	29	0140	N23W56	I	C							30	1720	40	II	SSC
	VIII	11	1920	N22E27	III+	C	13			10	I		14	1510	68	I	SSC
	VIII						26			4	I						
	IX						1			2	I		2	1158		II	SSC
	IX	3	0037	N20E87	III	B	3	08	7	8	III	F	4	1145	37	III	SI
	IX	16	1710	S21E66	I	C											
	IX	26	0530	S19W64	II+	C	26	08	2.5	4	II	F	29	0836	75	II	SSC
	X						4	1600		4	II		6	0237		III+	SSC
	X	11	0520	S18W36	II	C							13	2147	64	I	SI
	X	29	1020	N22E26	III	C	29			3	I						
	XI	10	1010	N29E28	III	B							12	1325	51		
	XI	11	0315	N29E12	II+	A	11	04	1	1/2	I	F	12	1846	40	III+	SSC
	XI	12	1323	N27W01	III+	B	12	1515	2	>3	III	G,F	13	1021	21	III+	SSC
	XI	14	0246	N27W19	II+	A	14	Masked			II	F	15	1304	34	II	SI
	XI	15	0207	N26W32	III+	A	15	03	1	>6	III	G,F	15	2155	20	III	
	XI	20	2017	N25W>90	I	B	20	2300	3	5	III	F	21	2147	26	II	SI
	XII	(5	1825	N27E68	III+)		8			2	I		7	1804	48	II	SSC

Year	Month	Solar Flare with Type IV Outburst					Polar Cap Absorption						Geomagnetic Storm				
		Onset Date	Time	Position	Imp.	Imp. of Type IV	Onset Date	Time	Δt_a (hrs)	Duration (days)	Imp.	Type	Onset Date	Time	Δt_m (hrs)	Imp.	Type
1961	II						13			1	I		13	0253		II	SSC
	II						18			4	I		16	0536		II	SSC
	III						17			3	I		Kp	>5			
	IV						14			1	I		13	1450		I	SSC
	VI~VII						VI/4			36	I						
	VII	11	1654	S06E32	III	B	11	2000	3	1	II	F	13	1113	42	III+	SSC
	VII	12	1000	S08E22	III+	B	12	1115	1	6	III	F	13	1113	25		
	VII	15	1520	N15E17	III	C		Masked			III	F	17	1825	51	III	SSC
	VII	18	0921	S06W59	III+	B	18	^{b}1000	1	5	III	F	20	0248	41	I	SSC
	VII	20	1600	S05W90	II	B	20	Masked		5	II	F					
	VII	24	0450	N15E18	III+	C	24			7	II	F	26	1950	63	III+	SSC
	VII	28	0230	N10W37	II	C											
	VIII						1			23	I		1	22.8		II	SG
	IX						7			2	I						
	IX	10	1950	N08W80	I	C	10	2315	3.5	2	II	F	13	1554	68	I	SSC
	IX						14			15	I		13	1554		I	SSC
	IX	28	2208	N13E30	III	B	28	2315	1	7	III	F	30	1847	45	III+	SSC
	XI	10	1434	N09W90	I+	C	10	1515	0.7	2	II	F					
1962	II	1	0902	N10W35	II	C	1	2030	11	2	II	S	4	0930	72	II	SI
	II						5			1	II						
	III	1	1640	S14W56	II+	C											
	IX	27	1505	N09W10	I-	C											
	X						6			9	I		7	2026		I	SSC
1963	II						9	1845		8	I		9	2232		III	SSC
	IV	15	1034	S10W07	II	C	15	1215	2	4	II	F	19	0317	89	I	SSC
	V	1	0525	N15E46	II	C	1	1200	7	3	I	(F)	2	2219	41	I	SSC
	V						29			4	I-		27	2028		I	SSC
	VIII	6	0855	N13W11	II	C	6	1115	2	2	I	F					
	VIII	9	2234	N07W80	I	C	9	(2315)	(0.7)	2	I	F					
	IX	15	0015	N15E75	II	A	15	^{b}1030	10	>1.5	I	S	16	2229	46		SSC
	IX	16	1430	N12E50	II+	B	16	1600	1.5	>2	I	F	19	0543	63	I	SSC
	IX	18	2230	N12E17	I	B	19	0543	7	2	I	F	21	1413		III+	SSC
	IX	20	2350	N10W09	II+	A	21	0300	3	3	III	F	22	1601	40	III+	SSC
	IX	26	0638	N13W78	III	B	26	1115	4.5	7	II	F	27	1942	37	II	SSC
	X						12			1	I		11	12			SG
	X	28	0230	N11W25	III	B	28	0815	6	2	I	F	29	1359	36	III	SSC
1964	III	16	1553	N06W75	II+	B											
1965	I						10	0900		1	II						
	II	5	1753	N07W25	II	C	(5	1840	1	2	I-	F)	6	1414	20	II	SSC
	X	4	0937	S21W30	II	B	4	1200	2.5	1/2	I-	F	7	0859		I	SSC

Notes:

1. Dates and times are in Universal Time (UT).
2. Durations of PCA's are measured in days.
3. Δt_a and Δt_m in hours stand for the delay-times of a PCA and a geomagnetic storm, measured from the onset of an associated flare.
4. PCA's are classified into three types, i.e. F-type ($\Delta t_a < 8$), S-type ($\Delta t_a \geq 8$), and others (no associated type IV-flare). The sign G stands for a ~ 10 Bev proton event.
5. SSC means a sudden commencement geomagnetic storm, SI a sudden impulse, and SG a gradual geomagnetic storm.

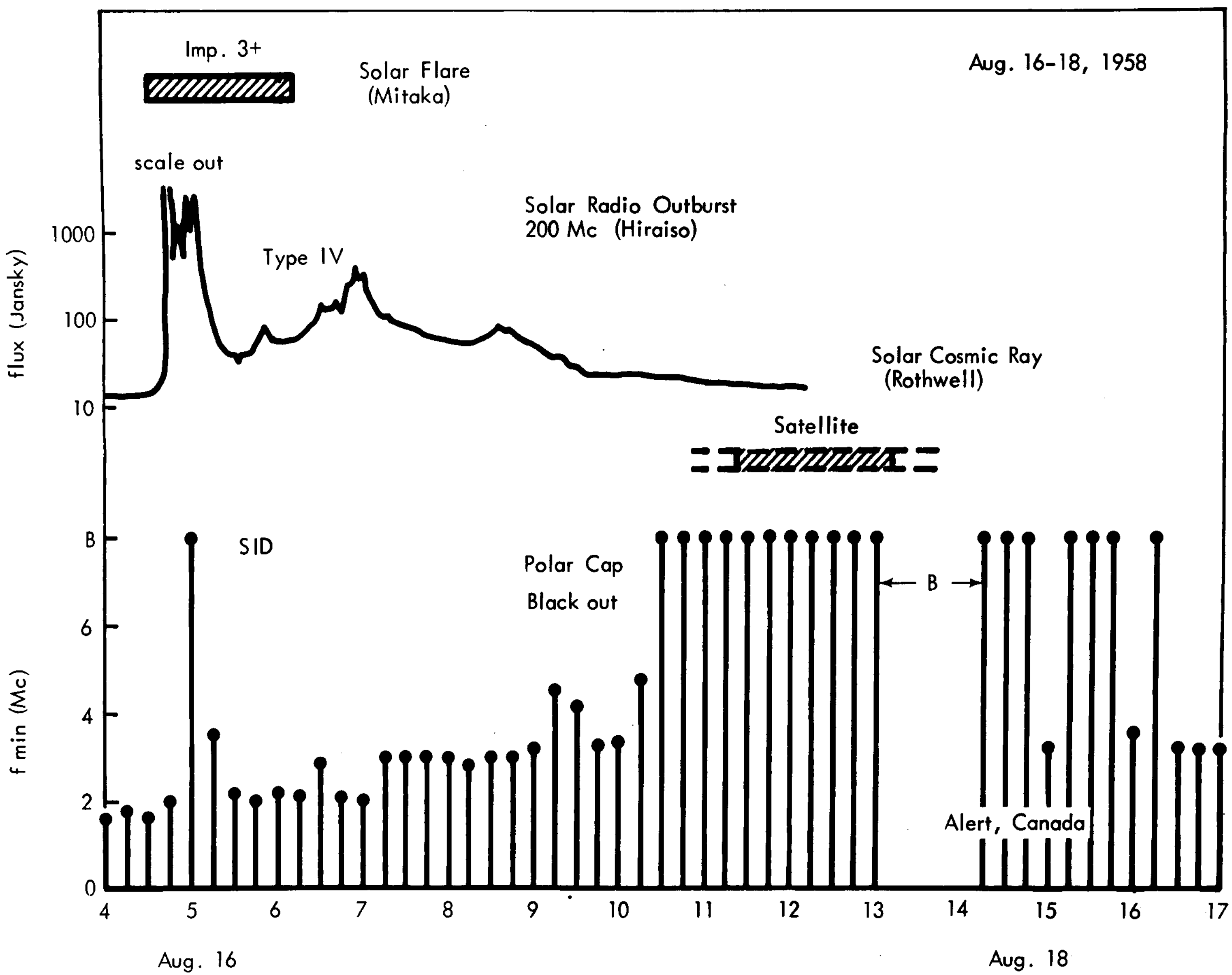

Figure 1. Solar-terrestrial events on August 16-18, 1958.

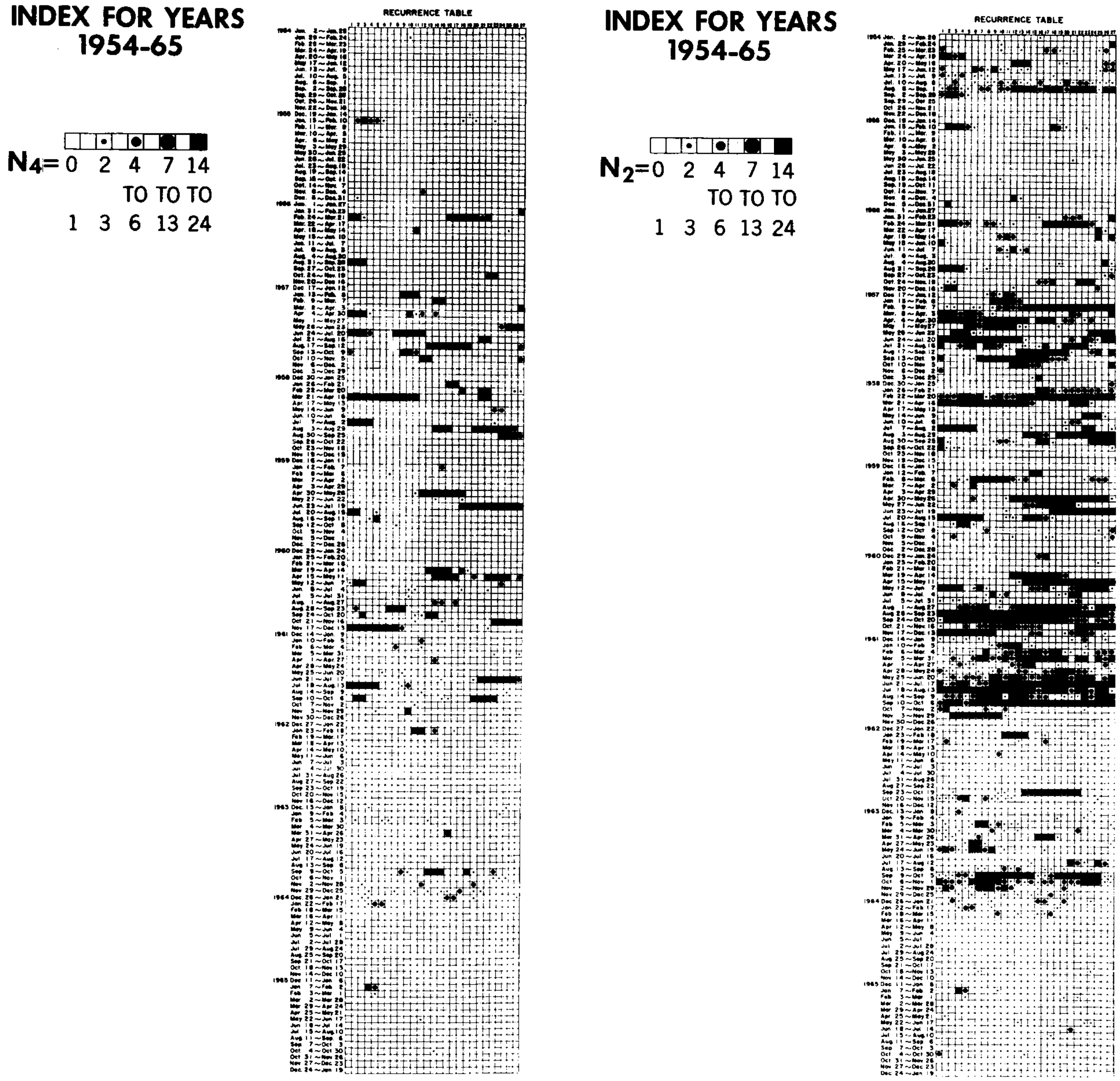

Figure 2. 27 days-recurrence tables of daily PCA-activity indices, N_4 (left) and N_2 (right)

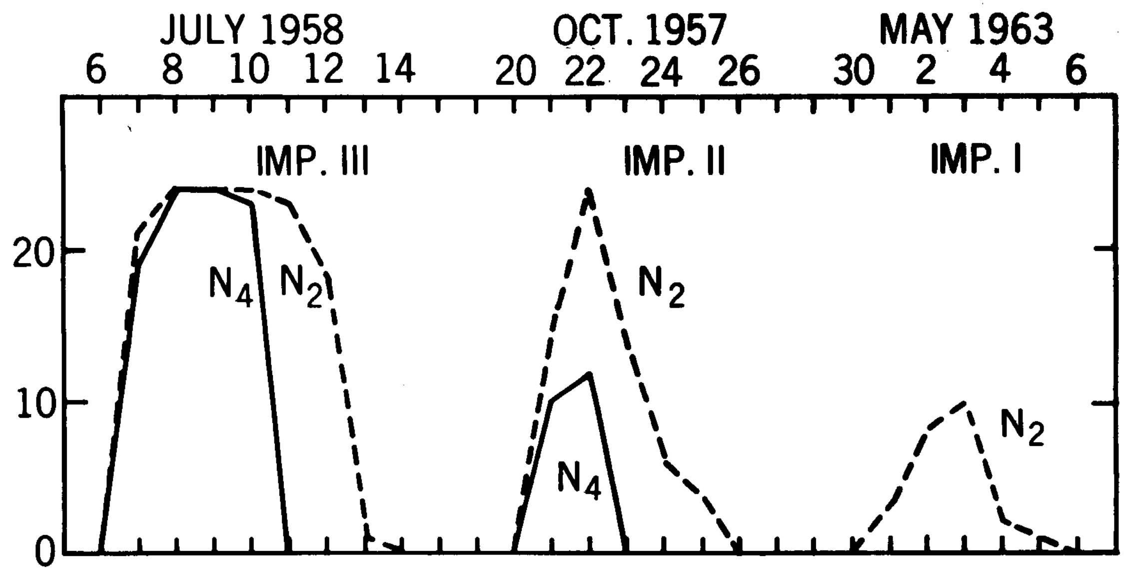

Figure 3. Three PCA events of different magnitudes as expressed by daily PCA-activity indices, N_4 and N_2.

A SCHEMATIC DYNAMIC SPECTRUM OF AN INTENSE SOLAR RADIO OUTBURST

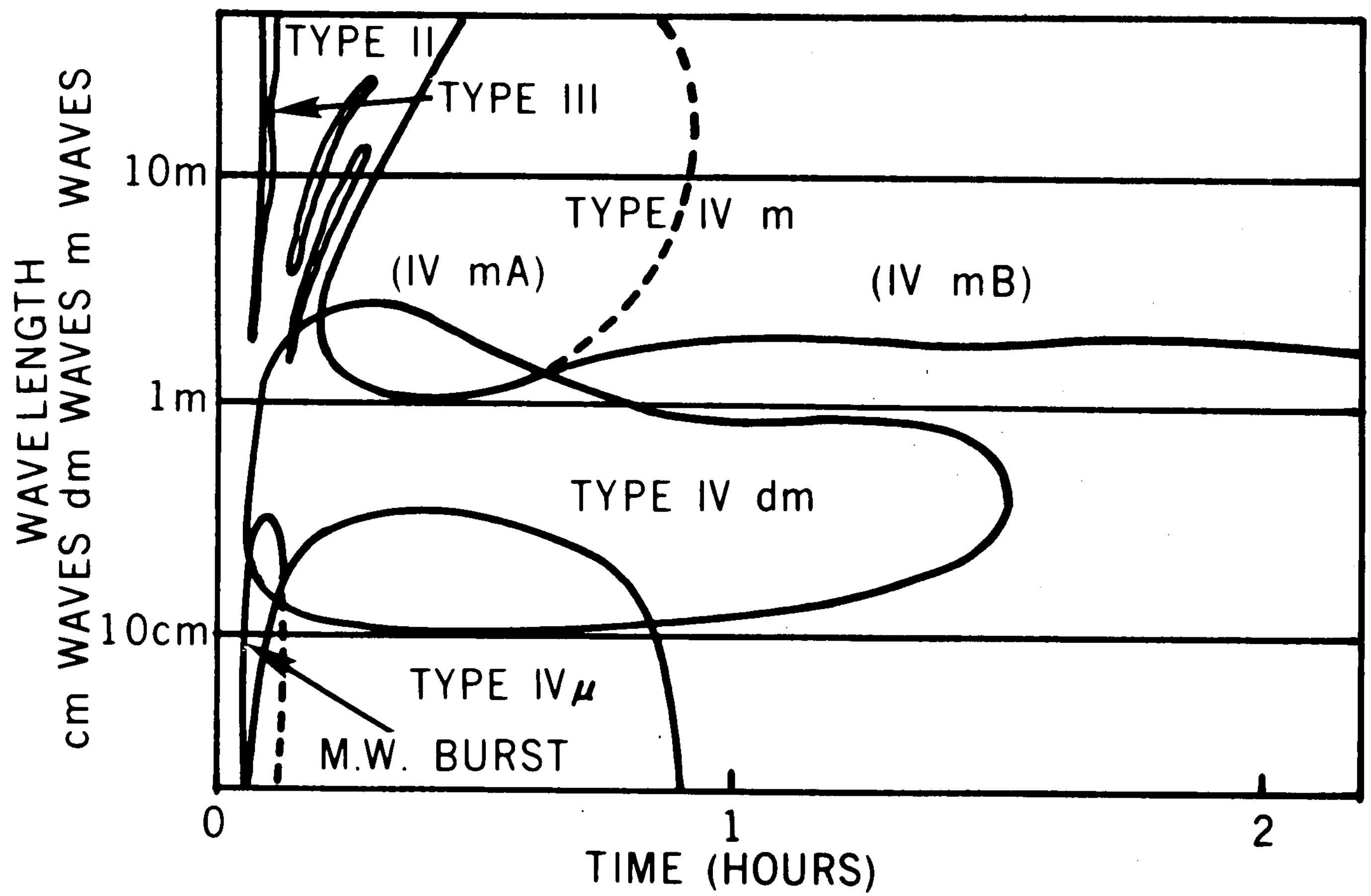

Figure 4. A schematic dynamic spectrum of an intense solar radio outburst.

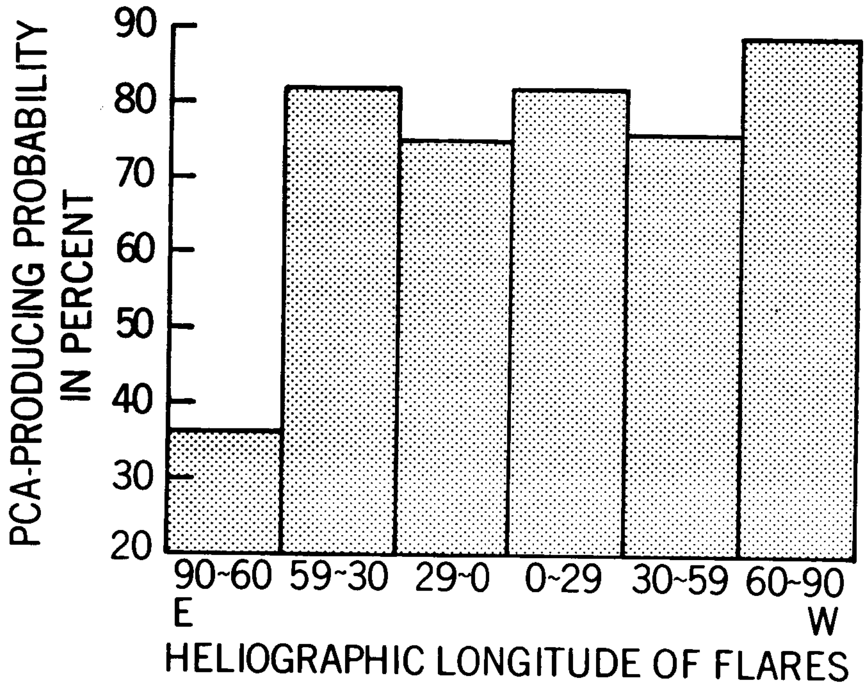

Figure 5. PCA-producing probabilities of type IV sources in six heliographic longitude intervals, inferred from the locations of associated flares.

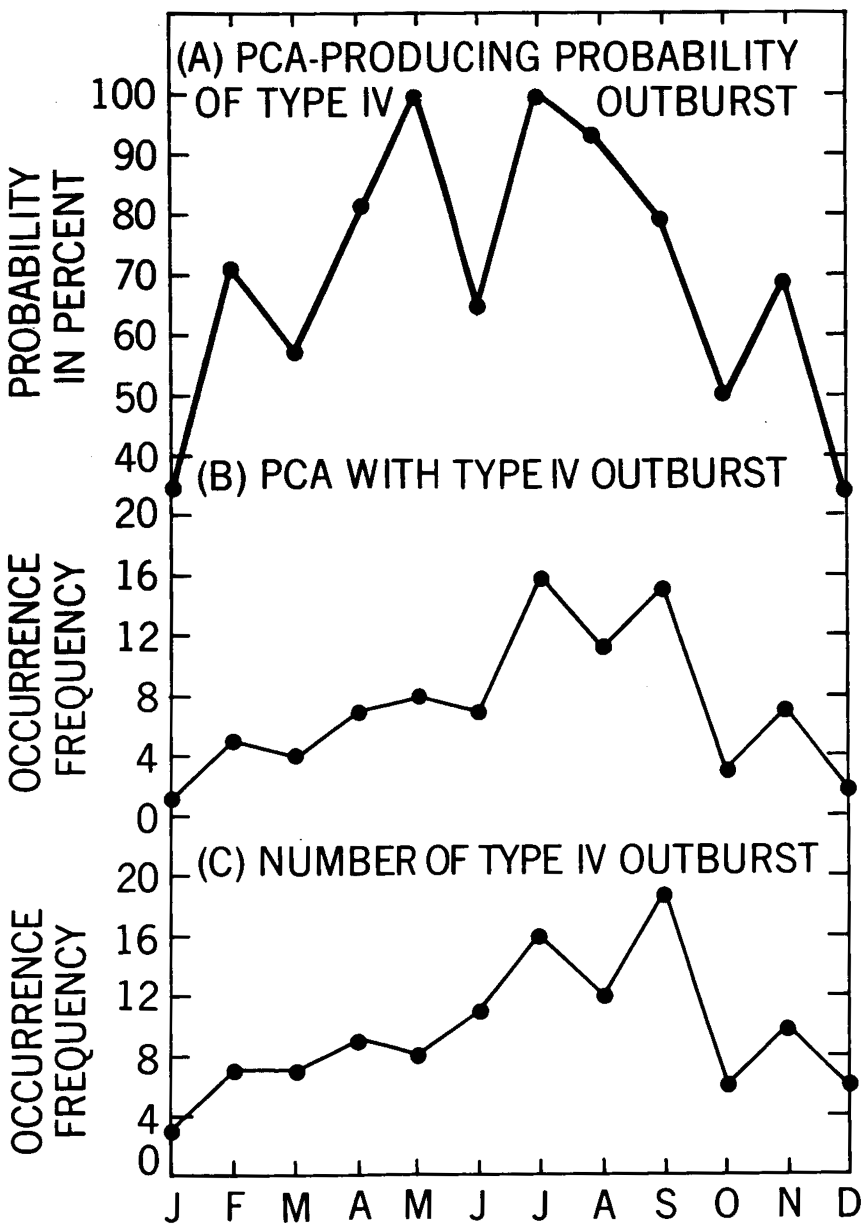

Figure 6. (A) PCA-producing probability of type IV outburst, (B) Number of PCA's Type IV, and (C) Number of type IV outbursts for each month, January through December.

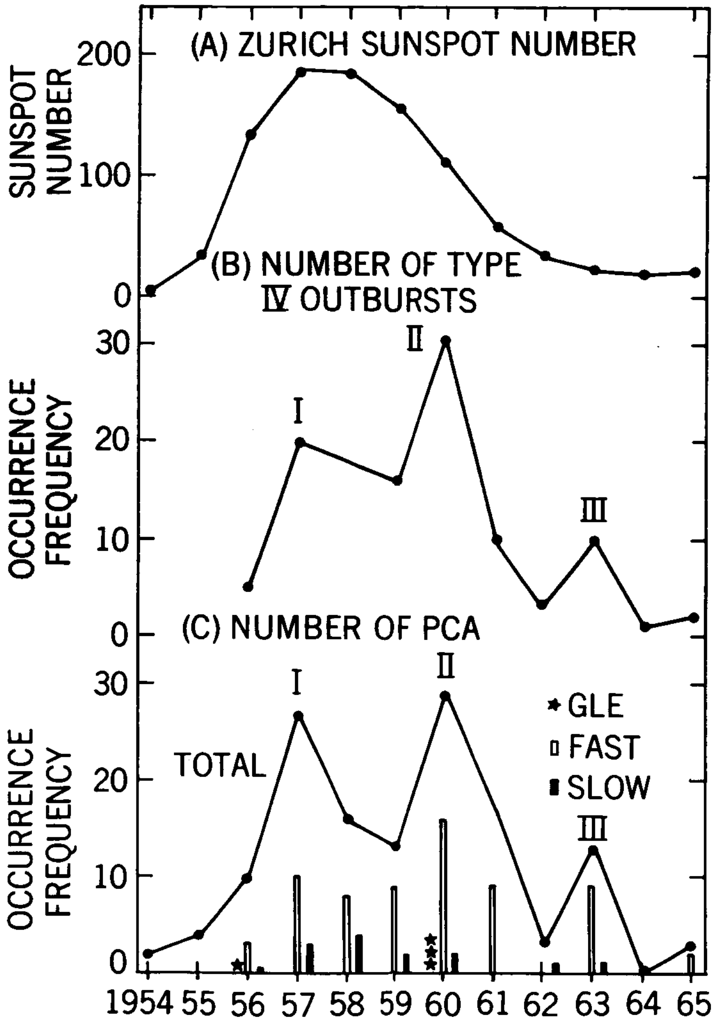

Figure 7. (A) Annual mean of Zürich sunspot numbers, (B) Number of type IV outbursts, and (C) Number of PCA's (total, identified GLE, fast- and slow-onset types), for years 1954–65.

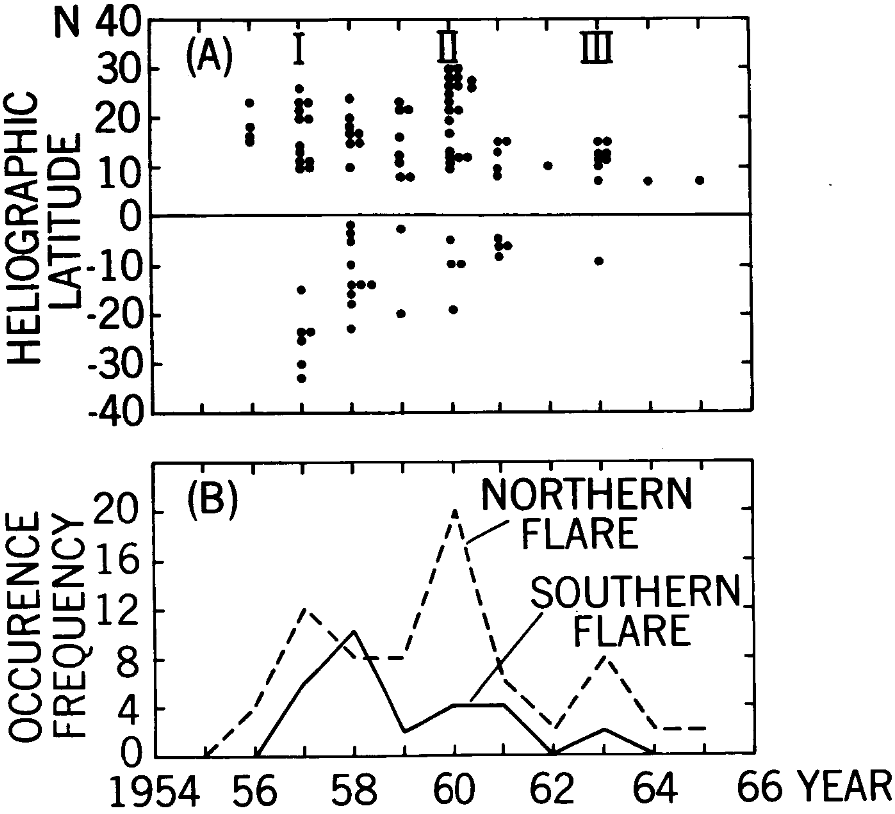

Figure 8. (A) Heliographic latitudes of PCA-producing flares and (B) Annual occurrence frequencies of northern and southern flares, 1954–65.

NORTHERN FLARE ▲ SOUTHERN FLARE ●

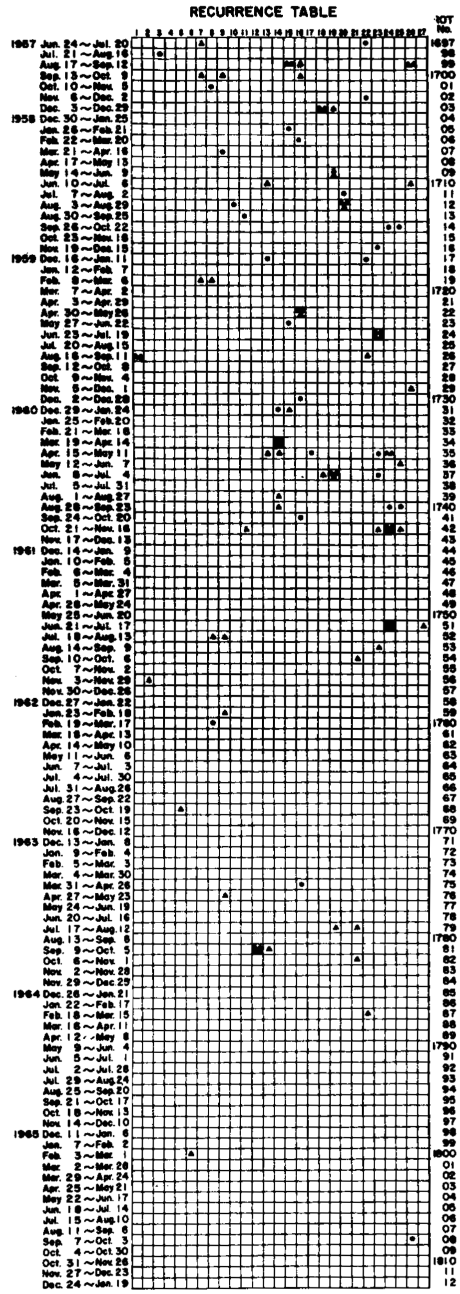

Figure 9. Distribution of CMP date of PCA-producing flares in the northern and southern hemispheres, on 27 days recurrence chart.

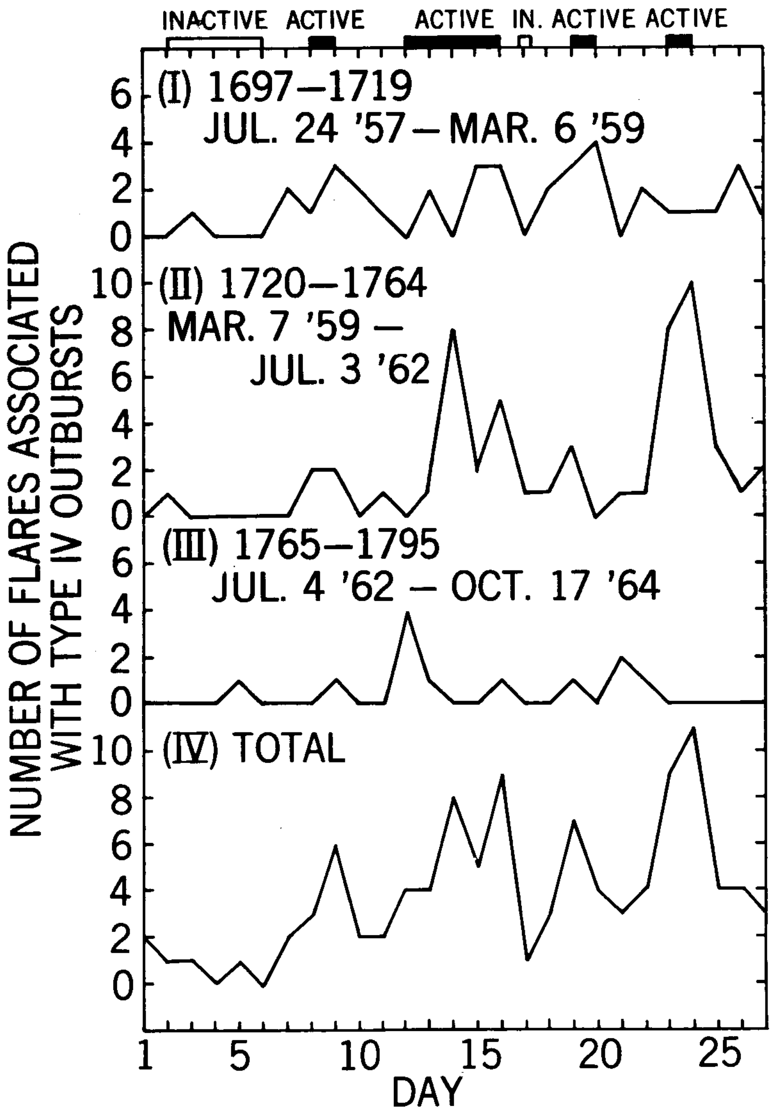

Figure 10. Longitudinal distributions of the CMP dates of type IV-sources, for solar rotation numbers (I) 1697-1719, (II) 1720-1764, (III) 1765-1795, and IV total.

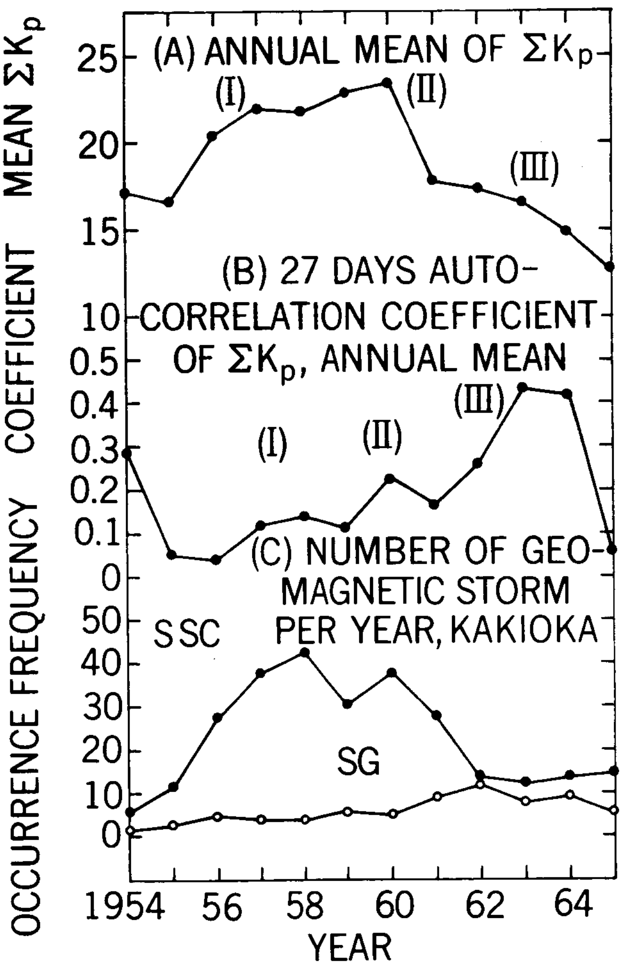

Figure 11. Solar cycle variations in (A) annual mean of ΣKp, (B) 27 days autocorrelation coefficient of ΣKp, and (C) numbers of SC and G-type geomagnetic storms observed at Kakioka, Japan.

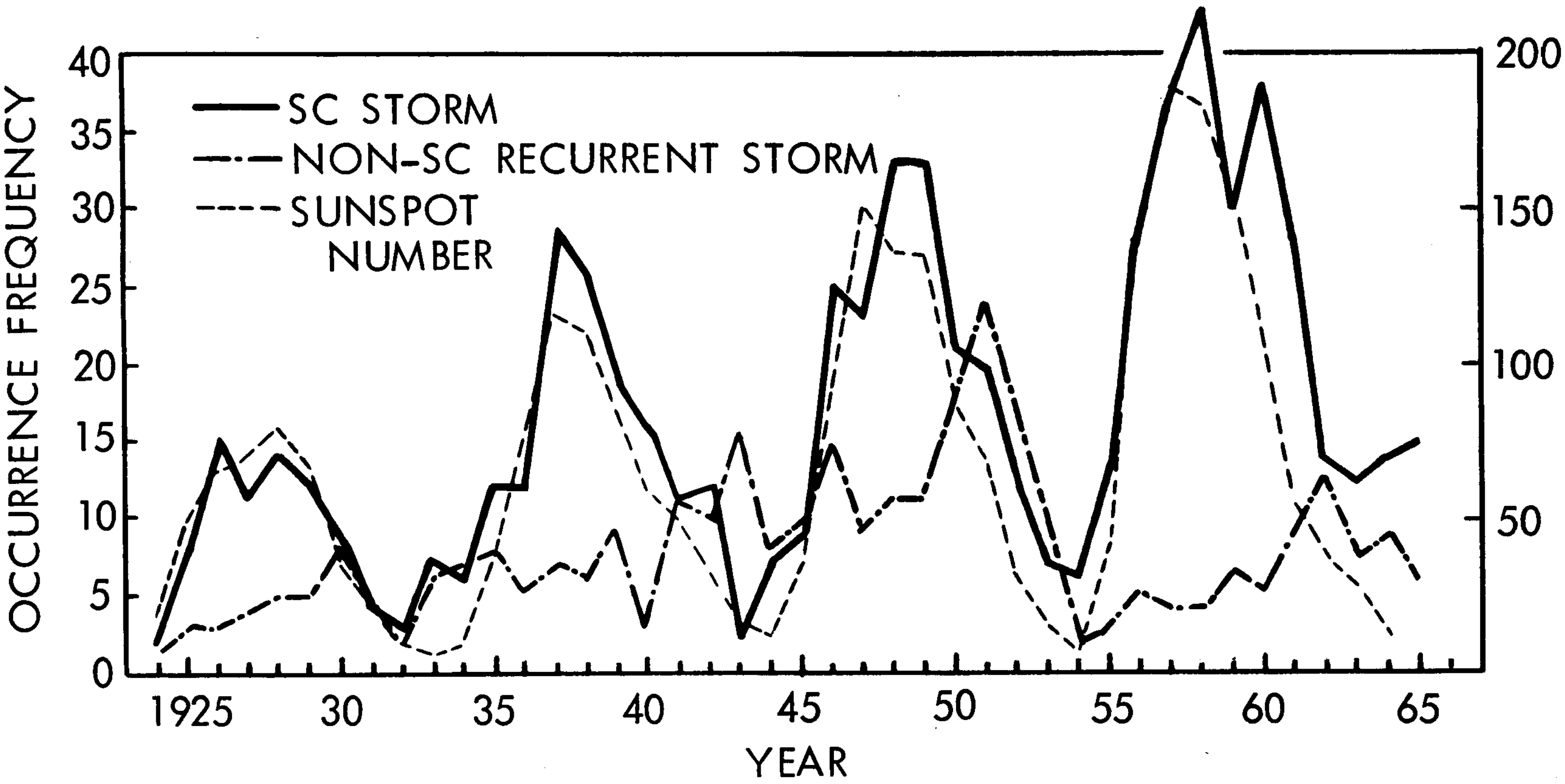

Figure 12. Occurrence frequencies of two kinds of geomagnetic storms per year, observed at Kakioka, and Zürich sunspot numbers, for the years 1924–65.

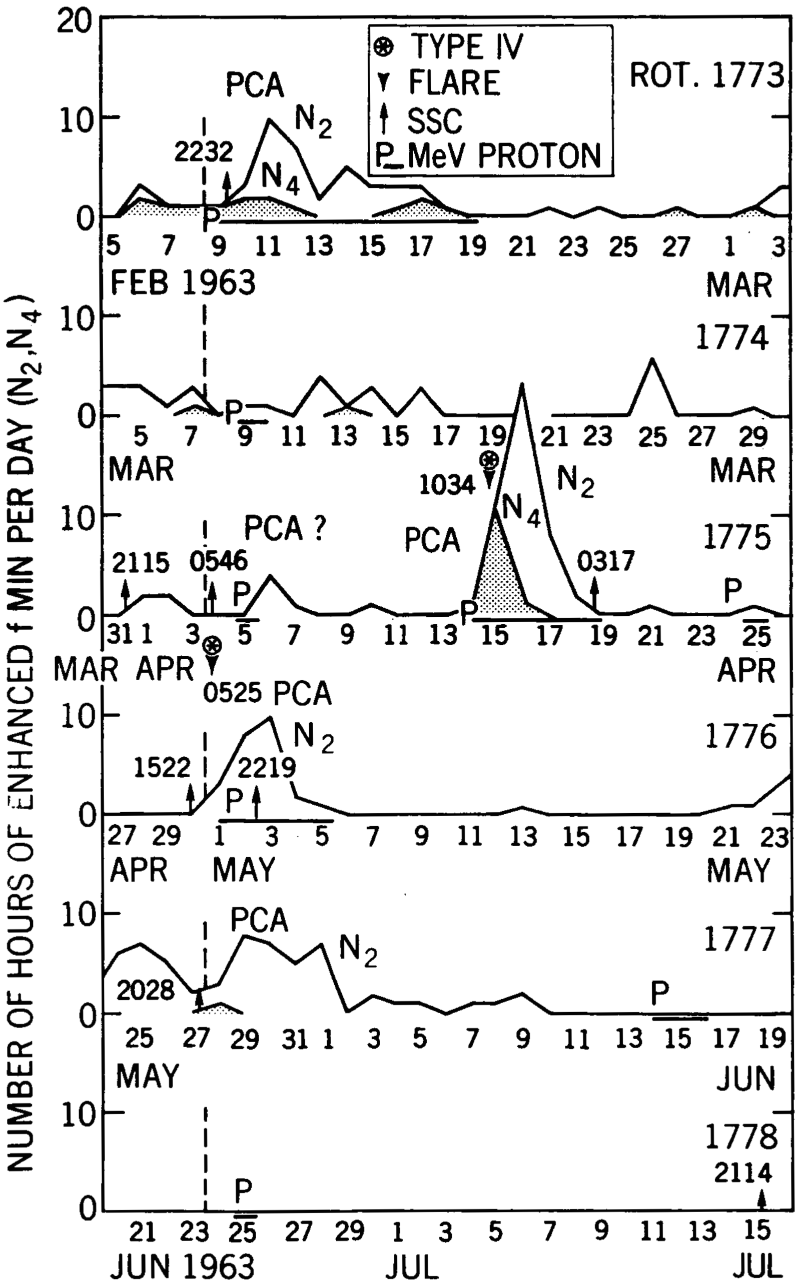

Figure 13. PCA's Mev proton events, flares, type IV outbursts, and the SSC's observed in solar rotations 1773–78. A recurrent series of PCA's or Mev proton events are notified by vertical dotted lines.

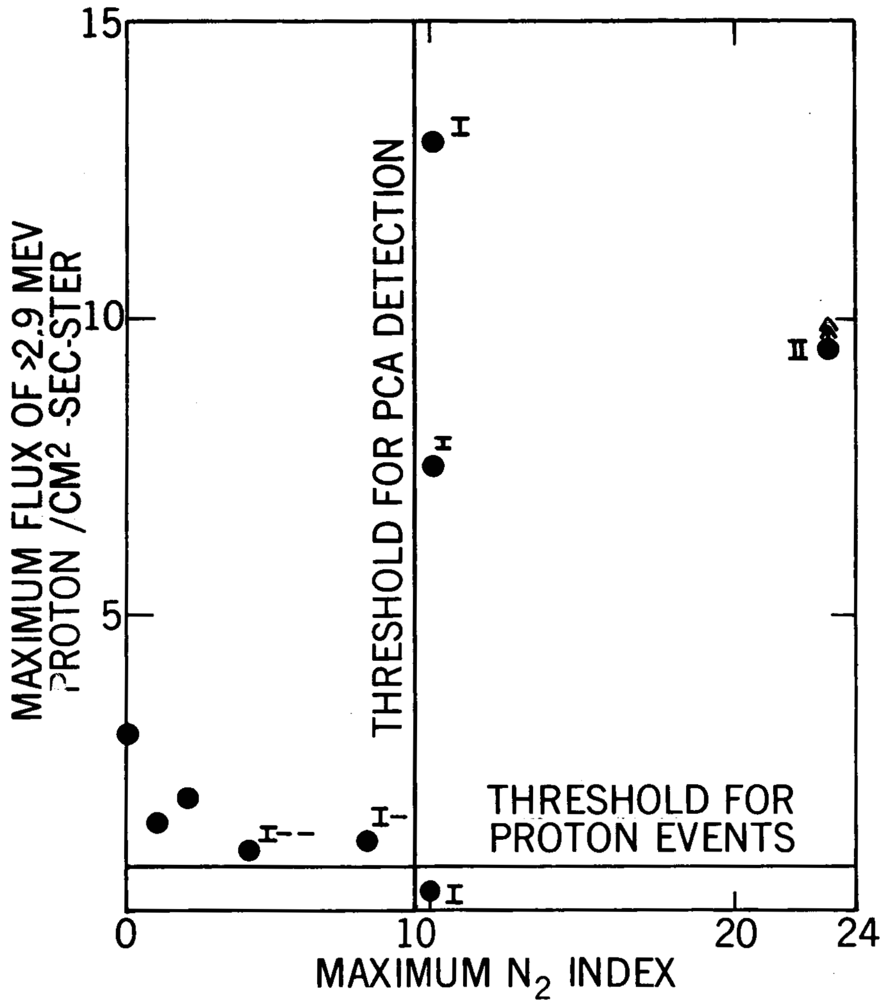

Figure 14, Relation between maximum flux of Mev proton events and maximum N_2 index of PCA given in Figure 13.

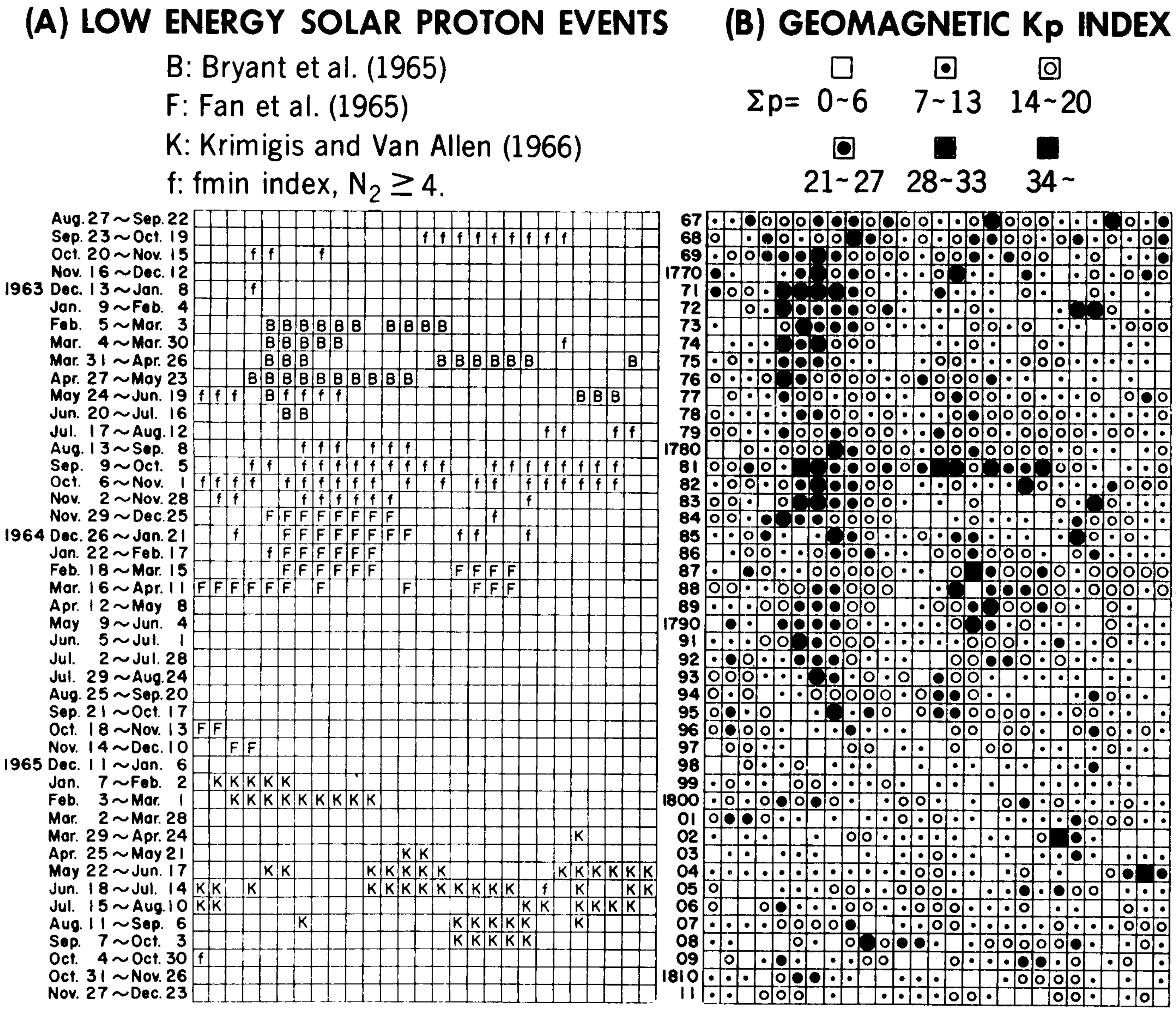

Figure 15. 27 days recurrent tables of (A) low energy solar proton events and (B) geomagnetic Kp index, for solar rotations 1767–1811.

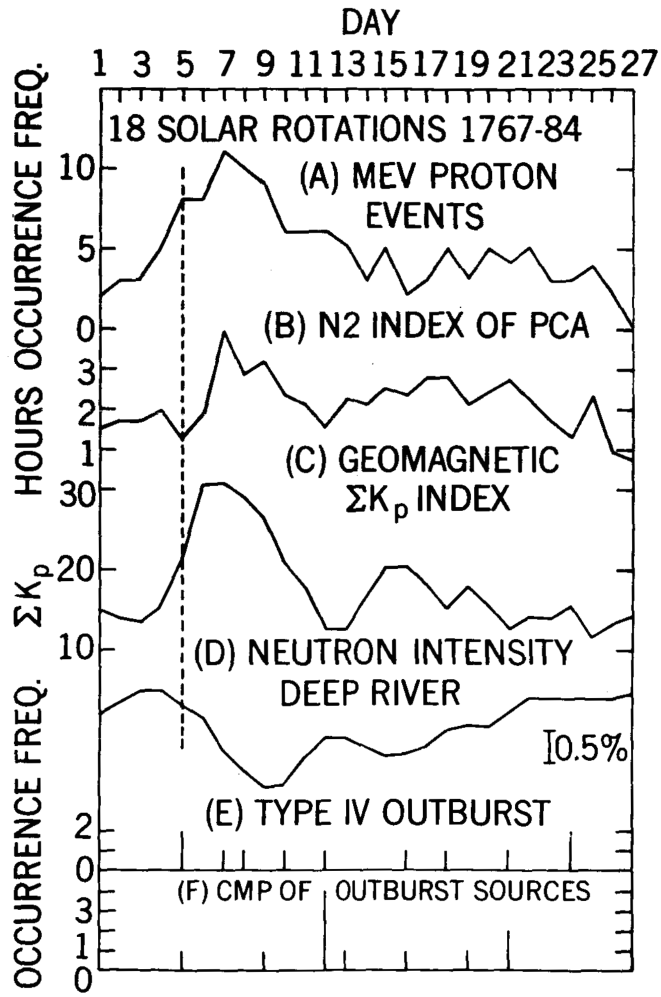

Figure 16. Occurrence frequencies of (A) Mev proton events and (B) N_2 index, average 27 days variations in (C) geomagnetic ΣKp index and (D) neutron intensity at Deep River (Mori et al., 1964), and occurrence frequencies of (E) type IV outbursts and (F) CMP dates of source regions, for 18 solar rotations 1767–84, i.e. August 27, 1962–December 25, 1963.

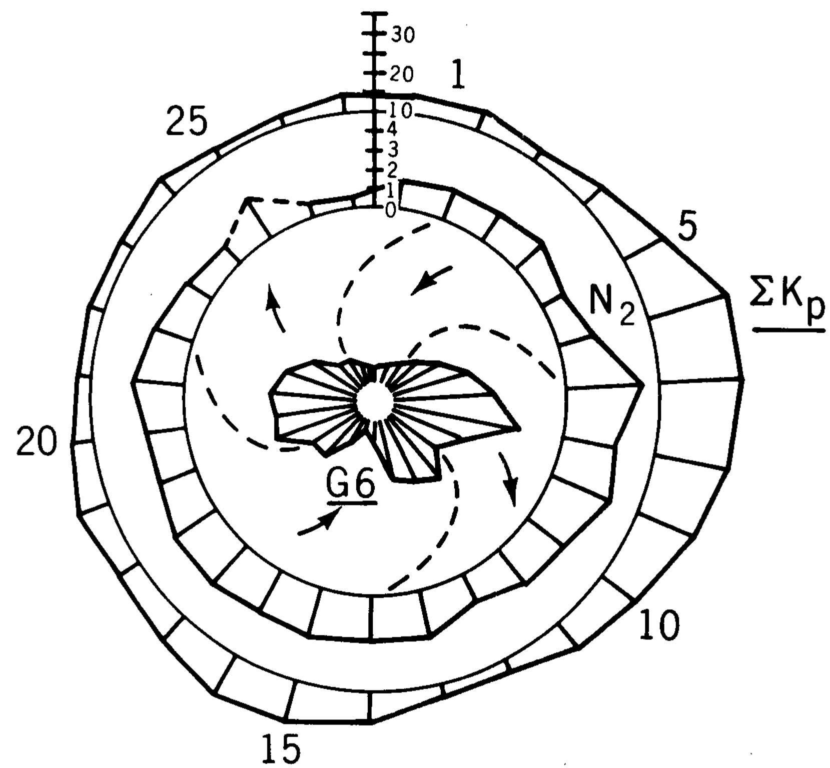

Figure 17. 27 days variations in ΣKp, N_2 index and coronal green line G6, and sector structure of the interplanetary space (Ness et al., 1964).

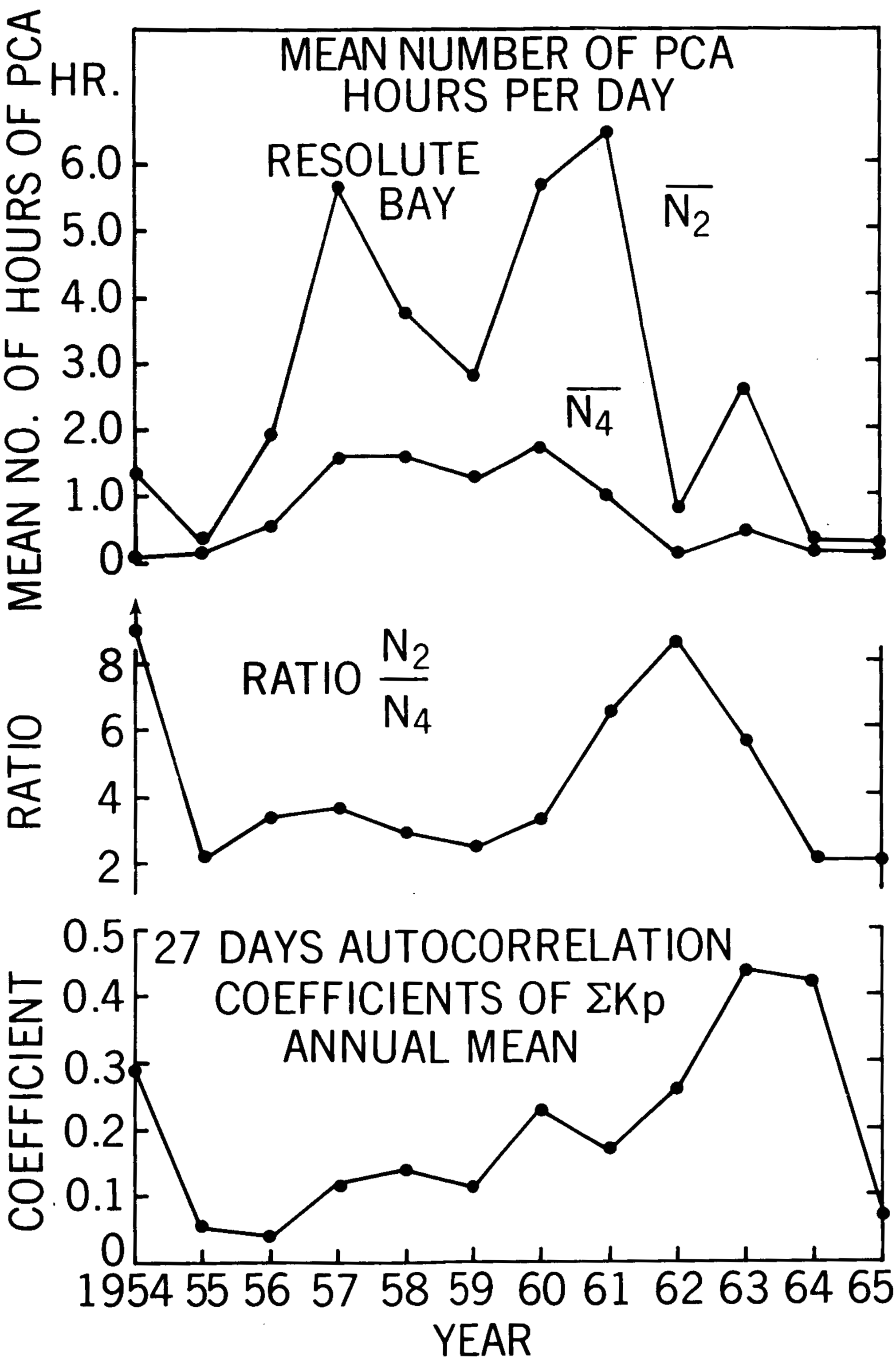

Figure 18. Solar cycle variations in (A) Mean N_4 and N_2 indices, (B) ratio N_2/N_4, and (C) 27 days autocorrelation coefficients of ΣK_p.